Zhang, K., and H.C. Frey, "Road Grade Estimation for On-Road Vehicle Emissions Modeling Using LIDAR Data," *Proceedings, Annual Meeting of the Air & Waste Management Association*, June 20-23, 2005, Minneapolis, MN

ROAD GRADE ESTIMATION FOR ON-ROAD VEHICLE EMISSIONS MODELING USING LIDAR DATA

05-A-1137-AWMA

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ABSTRACT

Vehicle Specific Power (VSP) can be used for second-by-second characterization of highway vehicle emissions based upon measurements with portable emissions monitoring systems (PEMS). VSP is calculated based upon vehicle speed, acceleration, and road grade to estimate engine power demand accounting for grade, rolling resistance, and aerodynamic resistance. Road grade is an important input but is more difficult to measure directly using PEMS compared to speed and acceleration. A method for estimating road grade is described based upon bivariate regression using Light Detection and Ranging (LIDAR) data. LIDAR data provides 3D coordinates of a geographic point on bare earth. An ArcObject-based macro was developed to buffer the LIDAR points onto a specified roadway segment and to calculate distances of each point along and from the centerline of the segment. For each segment, elevations of LIDAR data points were regressed on distances to fit a plane to road surface, yielding estimates of road grade and banking. Factors influencing errors in road grade estimates are discussed. Road grades estimated from LIDAR data and North Carolina Deportment of Transportation (NCDOT) design drawing data were compared in order to validate the LIDAR-based approach. The implications of accurate estimation of road grade with respect to emissions estimation were investigated based upon calculation of total emissions of NO_x, CO, hydrocarbons, and CO_2. Furthermore, the application of LIDAR data is demonstrated via a case study based upon PEMS data collected in the Research Triangle area. LIDAR data is shown to be reliable and accurate for road grade estimation for vehicle emission modeling.

Keywords: Road grade, emissions, measurement

INTRODUCTION

Vehicle Specific Power (VSP) can be used to quantify vehicle emissions related to different vehicles and operating conditions. VSP is defined as the instantaneous power per unit mass of the vehicle and can be calculated based upon speed, acceleration, road grade to estimate engine power demand accounting for rolling resistance, and aerodynamic drag. [1] Previous work has shown that VSP can be used for second-by-second characterization of highway vehicle emissions based upon measurements with portable emissions monitoring systems (PEMS). [2] For example, real-time in-vehicle emissions can be estimated by binning instantaneous VSP. [2, 3] Each VSP bin is associated with an average emission rate.

The calculation of VSP requires acquisition of speed, acceleration and road grade data. Road grade is an important variable with respect to emissions but is difficult to obtain compared to speed and acceleration. Speed and acceleration can be measured directly by PEMS while road grade cannot. Road grade can be approximated using Global Positioning System (GPS) data. However, GPS data can be imprecise for road grade approximation unless a sufficiently sophisticated (and costly) GPS system and data analysis procedures are used.

This paper is motivated by the need for more precise estimation of road grade via other means, with efforts to answer the following questions: (1) are vehicle emissions sensitive to road grade?; (2) by what means that road grade can be estimated?; (3) how accurate are road grade estimates; and (4) how can the estimated road grade be incorporated with PEMS data for vehicle emissions modeling purposes?

In order to answer these questions, the objectives of this paper are to: (1) evaluate the sensitivity of emissions to road grade; (2) evaluate alternatives for road grade estimation; (3) develop a reliable method for road grade estimation; and (4) validate the method via a case study for road grade estimation and emissions estimation.

METHODOLOGY

The methodological approaches used in this paper include: (1) sensitivity analysis to evaluate the importance of road grade with respect to VSP and emissions; (2) evaluation of alternatives for road grade estimation; and (3) development and validation of a reliable and accurate method for road grade estimation.

Sensitivity Analysis of Emission to Road Grade

The purpose of this section is conduct and interpret a sensitivity analysis of the relationship between emissions and road grade in order to assess the importance of road grade with respect to emissions. This is accomplished using a modal binning approach based upon VSP.

A generic VSP estimation equation is reported by EPA based upon coefficients typical of many light duty vehicles: [3]

$$VSP = v[1.1A + 9.81(\sin(a\tan(r))) + 0.132] + 0.000302v^3$$

where:

v = speed (m/s)

A = acceleration (m/s^2)

r = road grade (slope)

To evaluate the sensitivity of emissions to road grade, emissions are estimated using a VSP binning approach. [2] Each VSP bin refers to one of 14 "modes." Each VSP mode is defined by a range of VSP values, with some modes exclusive for negative values of VSP, and some exclusive for positive values of VSP. The definitions of VSP mode are shown in Table 1. For each VSP mode, an average emissions rate is estimated based upon PEMS or other second-by-second data. [2] For positive VSP, average emissions generally increase for increasing ranges of VSP.

Assuming zero acceleration in order to simplify the sensitivity analysis, road grade was varied from 0 to 0.06 and speed was varied from 0 km/h to 120 km/h. The corresponding VSP were calculated and categorized by mode thereby enabling estimation of average emissions. The sensitivity of VSP and emissions to road grade and speed are shown in Figure 1 and 2. Because acceleration was assumed to be zero, this analysis does not include negative values of VSP such as for deceleration, nor does it include all possible combinations of speed and acceleration that would produce different values of VSP. For a given speed, larger positive road grades lead to an increase in VSP, in turn leading to higher mode and average emissions rate. For example, estimated average emissions for a road grade of 0.06 are approximately a factor of two greater than for no road grade.

Table1. Definition of Vehicle Specific Power (VSP) Modes [2].

VSP mode	**Definition**
1	VSP < -2
2	-2 <= VSP < 0
3	0 <= VSP < 1
4	1 <= VSP < 4
5	4 <= VSP < 7
6	7 <= VSP < 10
7	10 <= VSP < 13
8	13 <= VSP < 16
9	16 <= VSP < 19
10	19 <= VSP < 23
11	23 <= VSP < 28
12	28 <= VSP < 33
13	33 <= VSP < 39
14	39 <= VSP

Figure 1: Sensitivity of VSP to Road Grade and Speed

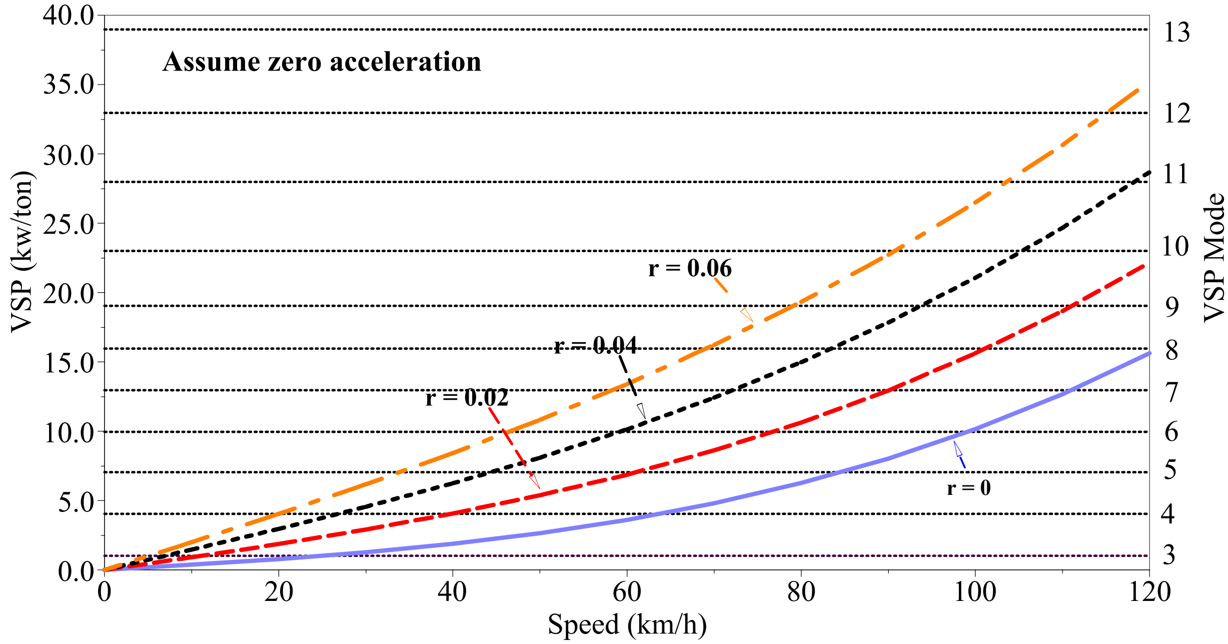
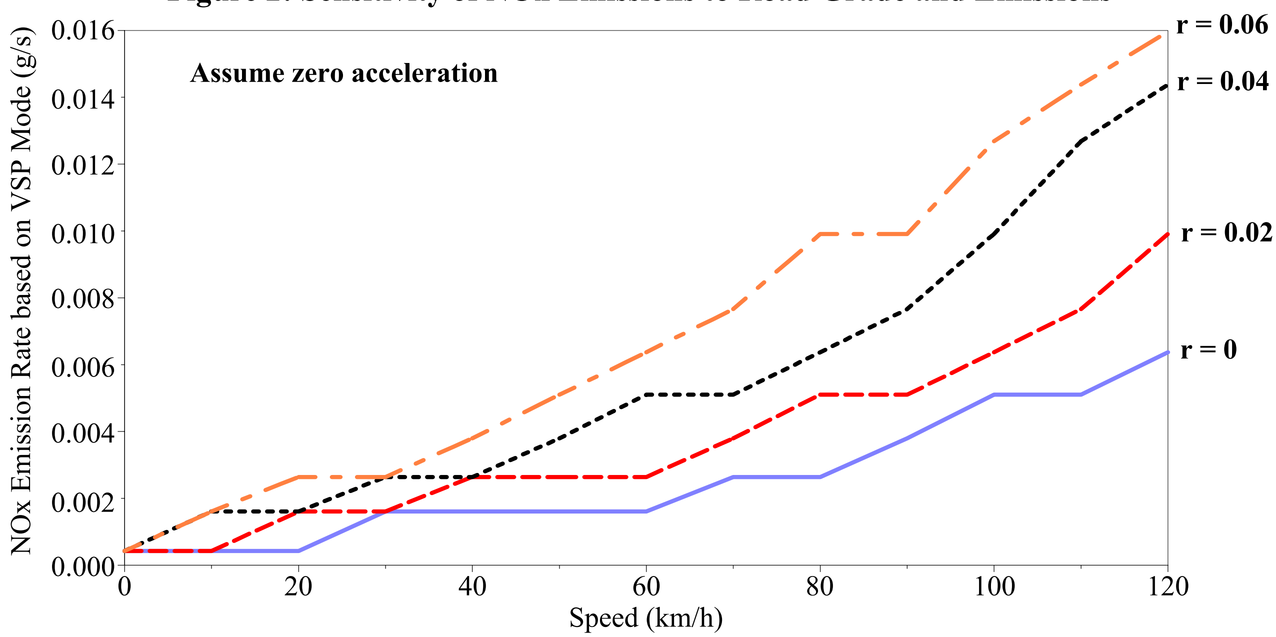


Figure 2: Sensitivity of NOx Emissions to Road Grade and Emissions



Evaluation of Alternatives for Road Grade Estimation

Road grade estimation methods are discussed and compared based upon design drawing data from the NC Department of Transportation (DOT), direct on-road measurement, GPS data, and Light Detection and Ranging (LIDAR) data. These alternatives were evaluated based upon their advantages and disadvantages.

Design Drawing Data

Road grade estimation using design drawing data may or may not be accurate because the roadway may not have been built exactly as shown in the pre-construction design drawings. Modifications to the roadway, such as regarding expansion of lanes, are not updated on the original design drawings. In addition, design drawings do not provide details regarding vertical curvature where there is a transition between different grades. Setting aside these potential limitations, road grade can be directly read from blue-print drawings. The roadway segment and its length are identified by station number, which indicates the cumulative distance from an assumed origin. For example, each blue-print corresponds to a roadway segment. The length of the roadway segment is obtained by subtraction of the smaller station number, at one end point, from the larger station number at the other end point. Although this method is conceptually straightforward, design drawings are not readily available for the full range of roadways to be included in on-road studies. Moreover, the use of design drawings is time consuming since they are not computerized and therefore must be reviewed manually. In this work, the main focus is on the use of design data for interstate highway projects as a benchmark for comparison with other methods.

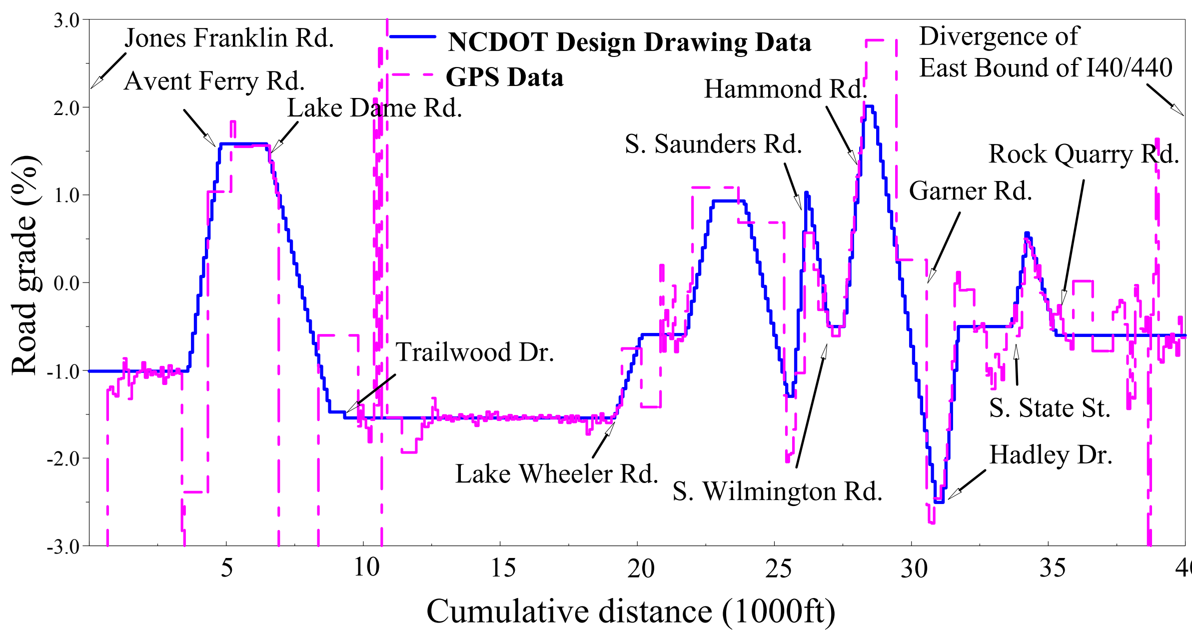
Direct On-Road Measurement

Direct measurement of road grade could be done using a digital level or similar device. However, this method is not safe for high traffic roads. The measurement process would be time consuming for lengthy routes. Furthermore, because of local imperfections in pavement, measurements at specific locations may not represent average road grades over longer distances.

GPS Data

A GPS system can be easily integrated into PEMS to collect x, y and z coordinates for the purpose of characterizing a route. GPS-based methods for road grade estimation have been discussed and applied. [4, 5] However, when GPS data are used to estimate road grade, a receiver with sufficient accuracy and precision is required. Furthermore, data correction to a base station and data post-processing, such as filtering, is typically needed. If any of these requirements are not met, this method will fail to provide a good estimate of road grade. Figure 3 presents results using an inexpensive GPS system compared to design drawing data for a specific segment of I-40. These GPS-based estimates are imprecise and deviate substantially from the design data. Thus this particular GPS dataset is not selected as a basis for road grade estimation.

Figure 3: Comparison of Available GPS Data and Design Drawing Data with Respect to Road Grade Estimation on a Segment of I-40 in the Research Triangle Park, NC Area

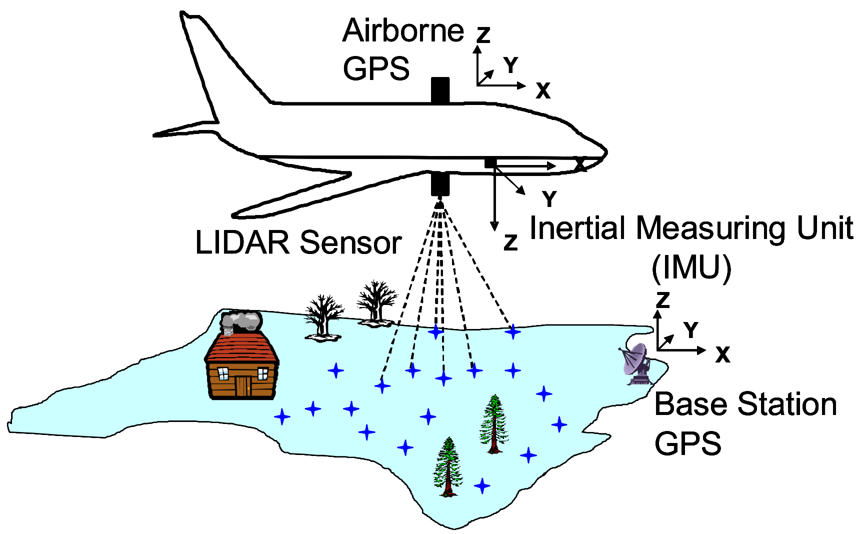


LIDAR

LIDAR is a promising technology for producing Digital Elevation Models (DEM). [6] It has been used for flood control, [7] road inventory collection, [8] and wide-topographic mapping. [9] The basic components of a LIDAR system include an airborne GPS, LIDAR sensor and Inertial

Measurement Unit (IMU) as shown in Figure 4. The LIDAR sensor measures the distance from the airplane to bare earth. The airborne GPS measures the x, y, and z coordinates of the moving LIDAR sensor in the air, and the coordinates are corrected using GPS base stations. The IMU establishes the angular orientation of the LIDAR sensor with respect to x, y and z in the flight. The system combines these data to provide accurate elevations of bare earth. [5]

Figure 4: A Simplified Schematics of a LIDAR Measurement System



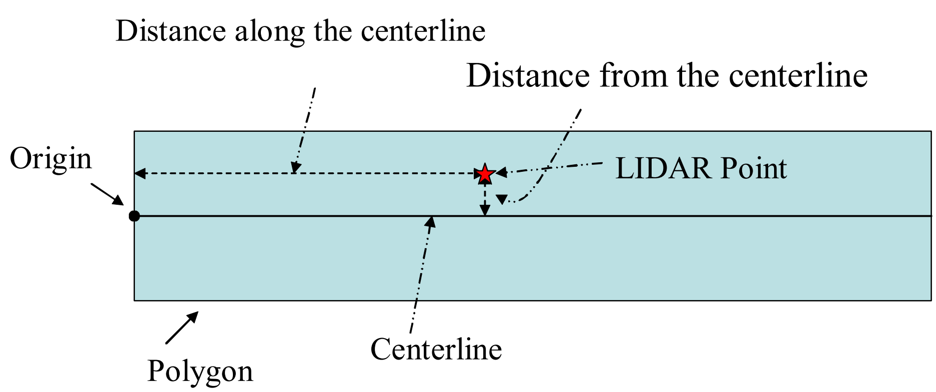
Compared to other methods, digital elevation data (DED) generated from LIDAR has many advantages, such as better accuracy, denser nominal point spacing, lower cost and ease of use.

LIDAR data are available for eastern North Carolina, including the Research Triangle Park (RTP) area in which the North Carolina State University (NCSU) PEMS-based project is in progress. Among the alternatives evaluated here, NCDOT design drawing data are not available for most of the RTP area; direct on-road measurement is discarded because of safety concerns, and the use of available GPS data has not yet to be proven to be reliable for road grade estimation. Therefore, LIDAR is selected as the preferred data source for road grade estimation. The LIDAR-based method will be discussed in detail in the following section.

LIDAR-Based Method for Road Grade Estimation

The use of LIDAR data to estimate road grade involves fitting a plane to digital elevation data for segments of roadways using regression techniques. For example, Pattnaik *et al* [8] used LIDAR-based surface models to estimate road grade and banking, which is the slope perpendicular to the direction of the travel. In their approach, Triangulated Irregular Network (TIN) surface models, which involve a particular type of data format for a Geographic Information System (GIS), were used to delineate the boundary of road segments of interest, and then a polygon (more specifically, a rectangle) was created to define the edges of roadway segment as shown in Figure 5. Distances for LIDAR points falling within the rectangle from and along the centerline of the rectangle were calculated based upon an assumed local origin. Finally, calculated distances were used for regression to estimate the grade and banking.

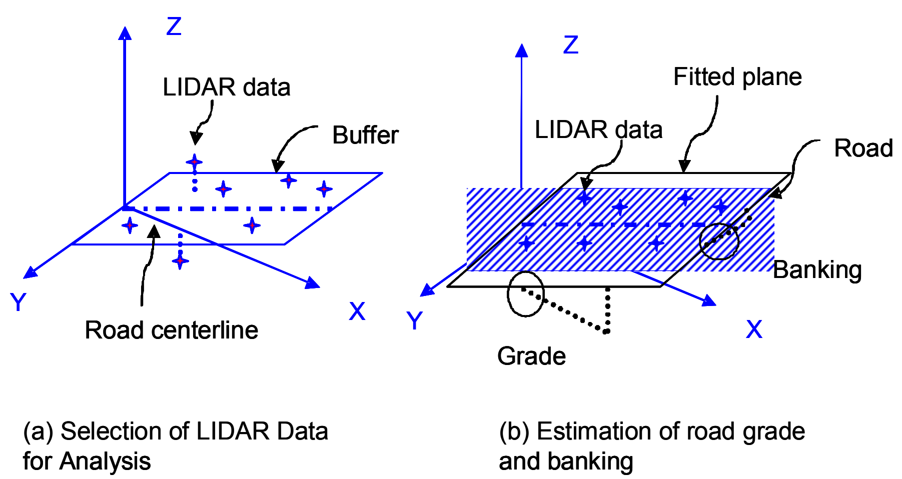
Figure 5: Delineation of Roadway Boundary



The method proposed in this paper also uses LIDAR data for road grade and banking estimation via regressions analysis. However, there are substantial differences between the method used in this paper and the one used by Pattnaik *et al*. These differences are: (1) buffers based upon prior knowledge of the width of roadway were used to define the analysis boundaries of roadways instead of TIN surface models; (2) the centerline of roadway in a map is used instead of a centerline inferred based upon a polygon defined using TIN surface models; (3) distances of LIDAR points from and along the centerline line of the roadway were calculated using an ArcObject based function; and (4) segmentation is used to diminish the effects of vertical curvature.

A schematic of the method used in this paper is shown in Figure 6. In Figure 6(a), a buffer was applied to the selected roadway segment based upon the width of the roadway and LIDAR data was projected onto the buffer. In Figure 6(b), a plane was fit to the roadway surface to estimate road grade and banking. Furthermore, segmentation should precede bivariate linear regression for accurate estimation of road grade. Segmentation and regression are separately discussed in the following sections.

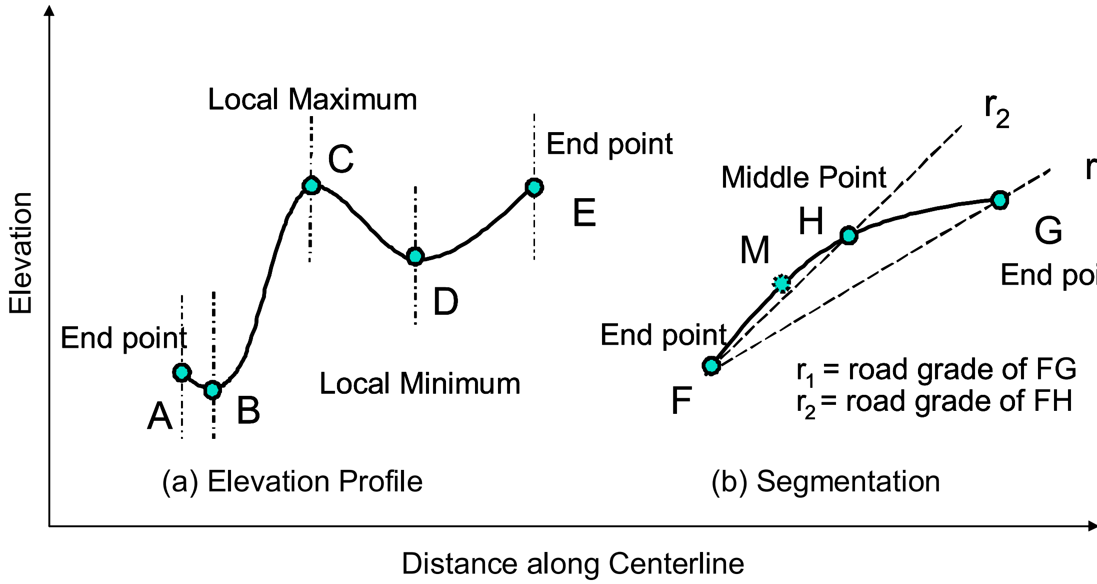
Figure 6: Schematics of Road Grade Estimation Using LIDAR Data.



Segmentation

The purpose of segmentation is to eliminate the effects of curvatures, especially vertical curvature, by creating segments that are approximately piecewise linear both vertically and horizontally. Simplified schematic diagrams that help illustrate the considerations and procedures for segmentation are shown in Figure 7. Figure 7 (a) shows the longitudinal cross-section of segment AE. Within segment AE, segments AB, BC, CD, DE have different changes in elevation and, hence, different road grades. Thus, it is not appropriate to fit only one surface plane to estimate the road grade for segment AE. In reality, segment AE has to be further sub-segmented. The procedures of segmenting include: (1) specify the end points of a roadway link and identify its local extremums by elevation to generate segments; (2) divide each segment into two equal subsegments; and (3) check the difference of estimated road grade between the originally selected segment and the equal subsegments. The sensitivity analysis reported earlier indicated that a difference in road grade of only 0.1% is not associated with a significant difference in emissions. Thus, as a criteria, if the road grades of two sub-segments differ by less than 0.1%, then there is no need to further divide the segment. In Figure 7 (b), if the difference of r1 and r2 is less than 0.1%, no further segmentation is necessary for segment AC. Otherwise, further segmentation is needed for segment FG. In addition, linear regression requires the assumption of normality of data points; hence each segment should be at least 100 ft long to guarantee sufficient LIDAR data points [8]. For subsequent statistical analysis, when defining segments, it is also desirable to limit the degree of horizontal curvature.

Figure 7: Methods of Segmentation of Roadway Segment



Bivariate Linear Regression

In order to infer road grade, a plane is fit to the roadway surface for each roadway segment using linear regression:

$Z = aX + bY + C + \varepsilon$

Where:

Z	=	elevation of LIDAR points buffered onto the road segment (ft)
X	=	distance along the centerline of the road segment (ft)
Y	=	distance from the centerline of the road segment (ft)
a	=	estimated road grade for specified road segment (slope)
b	=	estimated banking of the road segment (slope)
C	=	constant (ft)
ε	=	error term

The X and Y distances were calculated using ArcObjects® (ESRI, Inc) functions. Y distances were distinguished as positive and negative based upon the position of LIDAR point relative to the roadway centerline. A Y distance is positive if LIDAR point is to the left of the roadway centerline (looking down the road in the positive direction of the x-axis, where this direction is defined for each roadway segment), and the Y distance is negative if LIDAR point is to the right of the roadway centerline. The elevations of LIDAR points for each segment are regressed on their X and Y distances. Thus, the coefficient a is the road grade and coefficient b is the banking.

Factors Affecting Errors of Road Grade Estimates

Factors affecting errors of road grade estimates include accuracy of the roadway map, the accuracy and precision of LIDAR data, and segmentation relative to the magnitude of horizontal and vertical curvatures of roadway.

Accuracy of the roadway map refers to the extent to which roadway information, such as roadway position on the map, matches true or accepted values and corresponds with the position of the same feature in the LIDAR-derived data. For example, if the roadway position shown in the roadway map does not match its real world position, the estimates could deviate, unless the LIDAR data are subject to the same error (which is unlikely).

The accuracy of LIDAR is a function of airplane flying height, LIDAR sensor, quality of IMU data, and post-processing procedures. The accuracy evaluation of LIDAR is usually performed by comparing the positions in LIDAR dataset to georeferenced ground positions with higher accuracy from other datasets, such as aerial photograph, satellite imagery and ground survey. These datasets are recommended by National Standard for Spatial Data Accuracy (NSSDA). The evaluation accuracy of LIDAR data usually requires substantial work in data analysis and statistical tests, which is beyond the scope of the current work. The accuracy of LIDAR data used in this study is evaluated simply by comparing topographical features created by LIDAR data to those from digital orthophoto images in the study area. The digital orthophoto images were obtained by Wake County GIS services of North Carolina. The geographical features created from LIDAR data agree with those from the orthophoto images. For example, both data sources create the same road beds at approximately the same locations.

The precision of LIDAR data is quantified by root mean square error (RMSE). For example, RSME of LIDAR data used in this work is reported to range from 7.7 to 25 cm, which is much smaller than changes in elevation that are significant with respect to emissions.

Another consideration with respect to error in estimates of road grade is that if segments used for regression analysis are not piecewise linear, such as because of containing too much vertical curvature, then road grade estimates inferred from the linear regression approach are likely to be in error.

Validation of LIDAR-Based Method

The LIDAR-based method was used to estimate road grade for selected segments of I-40 and I-540 in the Raleigh, NC area. Estimated road grades were compared to NCDOT design drawing data. The comparisons of estimated road grades with NCDOT design drawing data for I-40 and I-540 are shown in Figure 8 and Figure 9, respectively.

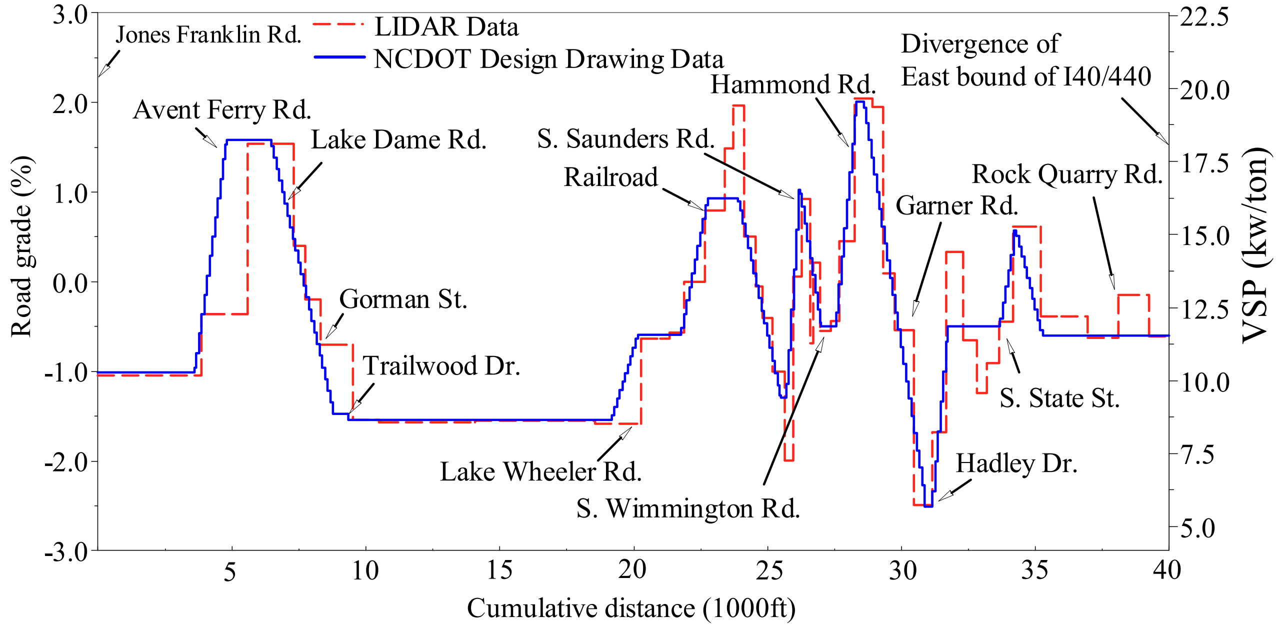
In Figure 8, road grade for a large section of I-40E from Jones Franklin Rd. to the I-40 and I-440 split in Raleigh, NC were estimated based upon LIDAR and design drawing data and the estimates were compared. In Figure 9, road grades for a lengthy section of I-540E from I-40E to Six Forks Rd. in the Raleigh, NC area were also estimated and compared.

Comparisons in Figure 8 show generally good agreement between the two sets of estimates. In Figure 9, comparisons in sections of 0 to 10,000 ft and 25,000 ft to 57,000 ft in distance show a generally good agreement between LIDAR data and design drawing data. For sections from 10,000 ft to 25,000 ft, there exist some discrepancies. The roadway is in a hilly area, and LIDAR data tend to capture more detailed changes in topography than design drawings do. The design drawings do not provide details regarding vertical curvatures when there is a transition between different grades. In order to account for vertical curvature when making inferences from the design drawing data, additional calculations are required that are based upon rules of thumb for typical highway design practice. Although these calculations were performed for the design drawing data shown in Figure 8, they were not performed for the design drawing data shown in Figure 0. Therefore, in Figure 9, road grades estimated from the in design drawings are shown to change sharply. This is just an artifact of the lack of accounting for vertical curvature, and not a real feature of the actual roadway.

In general, for most of the roadway segments, the relative difference between LIDAR data and design drawing data is less than 5% on a relative basis but the difference can be more than 100% for some segments that have small road grades (less than 1%). Although there are some discrepancies, the LIDAR-based estimates capture the major changes in road grade. Thus, the LIDAR-based method is deemed to be sufficiently reliable and accurate for road grade estimation.

For purposes of assessing the emissions implications of road grades on the selected sections of highway, VSP was estimated and then used to determine the average emission rate for the corresponding VSP-based emissions mode at each location along the highway, using the data in Figure 8 as an example. To simplify the calculation of VSP, a constant speed of 102 km/h (70mph) is assumed, for an idealized case of steady-speed driving during uncongested traffic. For small road grades, VSP is approximately a linear function of road grade. Thus, Figure 8 depicts VSP on the right vertical axis and road grade on the left vertical axis at each location along the highway.

Figure 8: Comparions of LIDAR Data and NCDOT Design Drawing Data with Respect to Road Grade Estimation on a Segment of I40E in the Raleigh, NC



Note: VSP is calculated assuming a constant speed of 102km/h.

Figure 9: Comparion of LIDAR Data and NCDOT Design Drawing Data with Respect to Road Grade Estimation on a Segment of I540E in Raleigh, NC

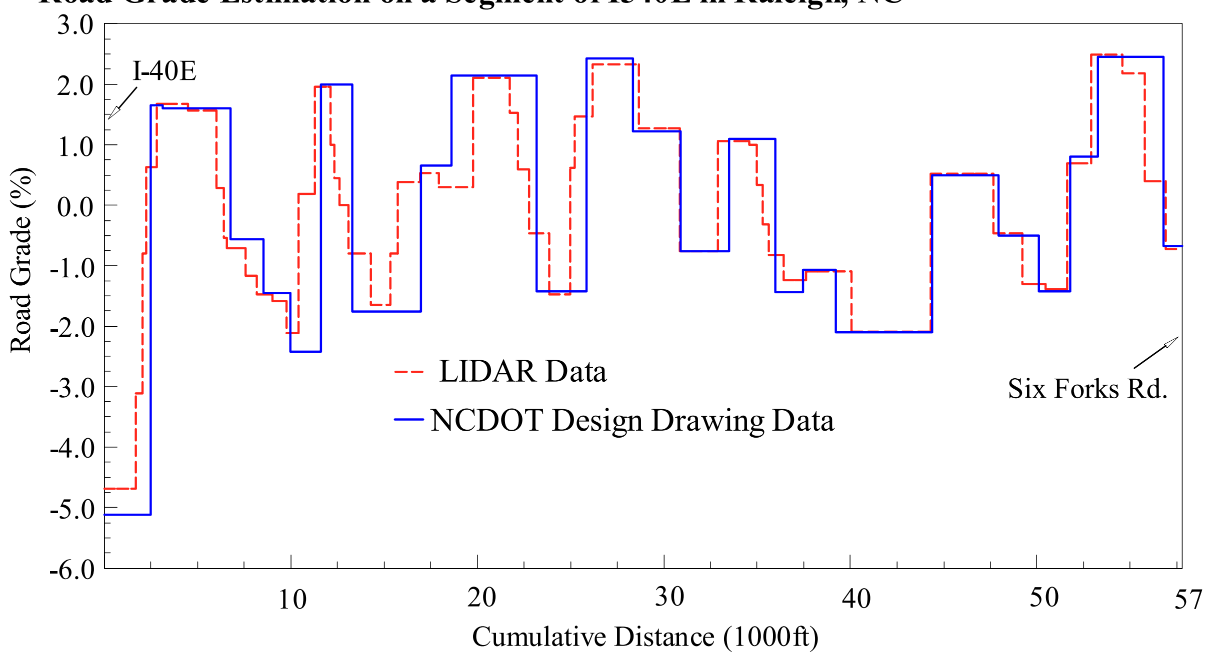


Figure 10 depicts the VSP modes, corresponding to various ranges of VSP that would occur at different locations along I-40 for a vehicle traveling at constant speed. One curve depicts

VSP estimated based upon NCDOT design drawing data and the other depicts VSP estimated based upon LIDAR data. In some cases, even though the road grade estimates differ, both data sources lead to selection of the same VSP-based driving mode, and thus would produce the same average emission estimate at a given location (e.g., this occurs at a cumulative distance of 38,000 ft). In some cases, difference in road grade estimates lead to a difference in the choice of VSP-based driving mode. In some cases, adjacent modes are selected (e.g., at about 9,000 ft, Mode 6 is selected based upon NCDOT design drawing data and Mode 7 is selected based upon LIDAR data). In very few cases, there are large differences in the selection of mode, such as at 5,000 feet.

The implications of VSP estimates and selection of VSP modes are summarized in a comparison of total emissions estimates for the entire section of highway as given in Table 2. The relative difference in emissions estimates for CO_2, NO_x, Hydrocarbons, and CO is less than one percent when comparing the LIDAR-based approach to the NCDOT design drawing-based approach. This implies that the amount of error in the emissions estimates can be less than the error in VSP estimates, and that for a sufficiently long section of roadway, both approaches produce essentially the same emission estimate. Of course, at specific locations, the errors can be greater.

Figure 10: Comparison of VSP and VSP Mode Profile for a Segment of I40 in Raleigh, NC Assuming a Constant Speed of 102km/h using LIDAR Data and NCDOT Design Drawing Data

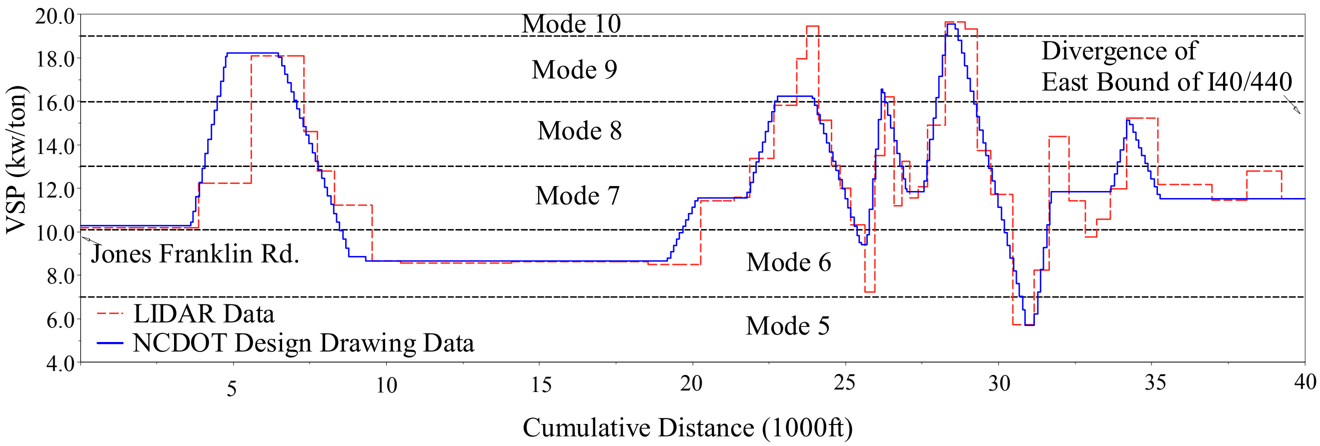


Table 2. Estimated vehicle emissions along a testing route

	CO (g)	CO_2 (g)	HC (g)	NO_X (g)
LIDAR Data	12.3	1867	0.81	2.06
NCDOT Design Drawing Data	12.2	1860	0.82	2.04
Relative Difference (%)	0.91	0.37	-0.43	0.79

Note: Vehicle assumed to have mileage greater than 50,000 and engine size less than 3.5L.

Application of LIDAR-Based Road Grade Data to In-Use Emissions Estimation

A key question is how to incorporate estimated road grade with PEMS data for vehicle emissions modeling purpose. For this purpose, road grades estimated using the LIDAR-based method are mapped to collected PEMS data based upon the cumulative driving distance and segment length. Cumulative driving distance is estimated using the speed profile from PEMS data, and the segment length is the length of the roadway on the map. Estimated road grade was matched to each collected second-by-second PEMS data point assuming the equality of cumulative driving distance and segment length. Doing so, vehicle operating data can be combined with road grade for VSP calculation, and hence used for vehicle emissions modeling. The method for estimating road grade associated with speed, acceleration, VSP and VSP mode is illustrated in Figure 11 using a PEMS dataset for the RTP area.

Figure 11a shows a road grade profile for a PEMS data set for a segment of I-540E from I-40E to Six Forks Road. This profile was obtained by mapping LIDAR-based road grade data onto the PEMS data set. The time shown on the x-axis is the elapsed time of driving along the selected route, from I-40 to Six Forks Road. The measured speed profile for a vehicle driven on this roadway is shown in Figure 11b, and the acceleration profile calculated from the second-by-second speed profile is shown in Figure 11c. For reference purposes, the cut-off points for some of the VSP-based modes are shown in Figure 11d.

VSP varies from approximately -40kw/ton to 60 kw/ton and the choice of VSP mode ranges from as low as Mode 1 (for negative values of VSP) to Mode 14 (for large positive values of VSP) during the trip segment. However, for most of the trip segment, the mode typically ranges between Mode 4 and Mode 11. Variation of VSP mode leads to variation of emissions, hence, occasionally vehicle emissions can be extremely high (or low) during the trip depending on the VSP values. When the road grade is relatively constant, VSP is mainly influenced by speed and acceleration, and when the speed is relatively constant, VSP tends to vary with change of road grade. Hence, the short-term episodes of VSP mode depend on the episodic vehicle operating conditions.

Figure 11a: Dynamically Matched Road Grade Profile for a Segment of I540E in the Research Triangle Park, NC Area

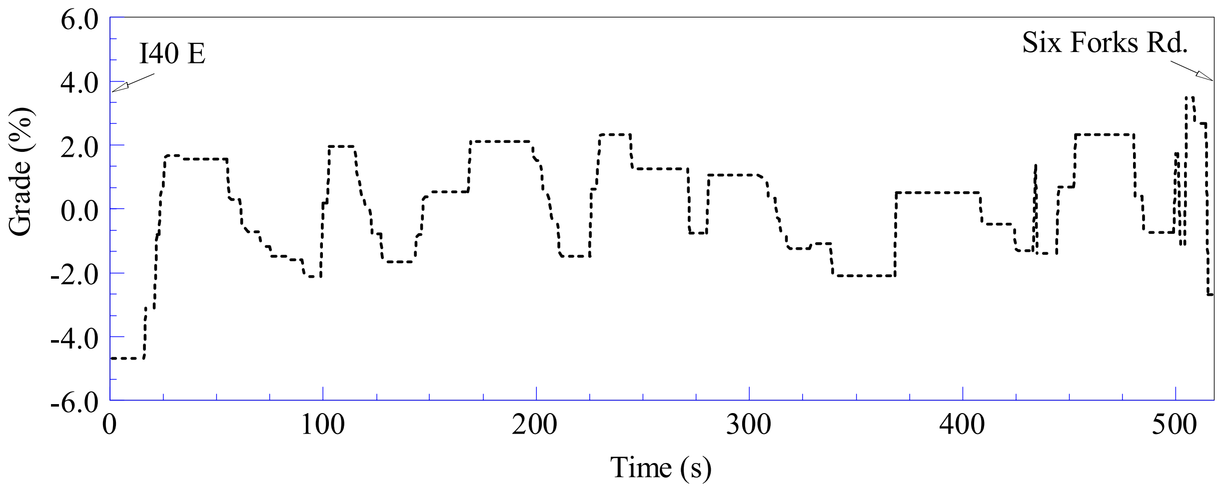


Figure 11b: Speed Profile for a Segment of I540E in the Research Triangle Park, NC Area using Portable Emissions Measurement System

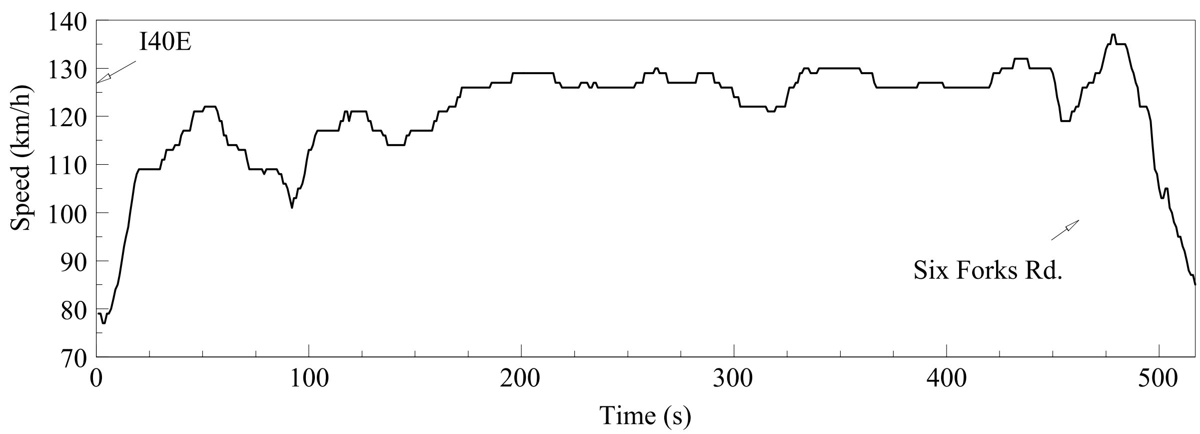


Figure 11c: Accleration Profile for a Segment of I540E in the Research Triangle Park, NC Area using Portable Emissions Measurement System

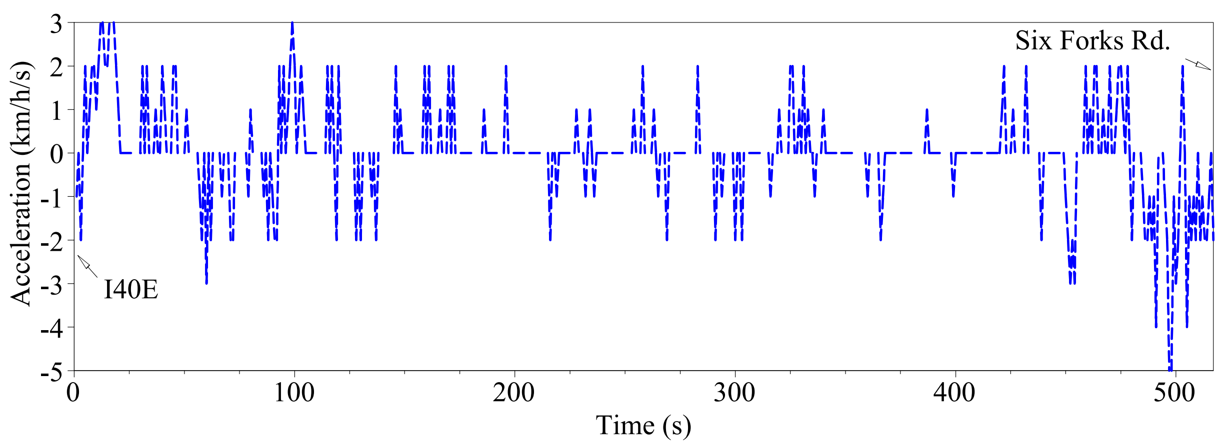
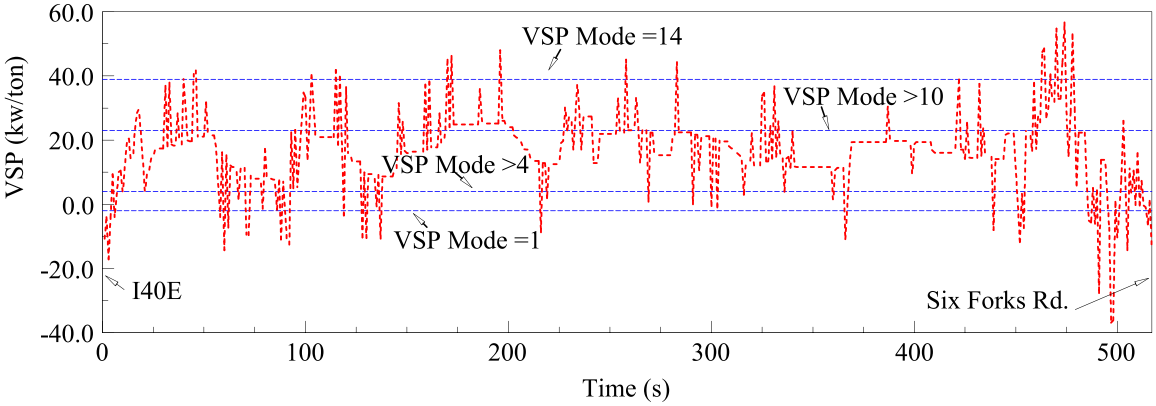


Figure 11d: VSP and VSP Mode Profile for a Segment of I540 E in the Research Triangle Park, NC Area using Portable Emissions Measurement System and Matched Road Grade



CONCLUSION

From case studies shown in this paper, both VSP and emissions are sensitive to road grade. Accurate road grade information is useful for VSP calculation and accurate emissions estimation. A LIDAR-based method has fewer limitations and was shown to be sufficiently reliable and accurate for purposes of emissions estimation. As an example case study, estimated road grades using LIDAR-based method were incorporated with PEMS data for VSP calculation on a second by second base. Thus, the feasibility of incorporating LIDAR-based road grade estimates with in-use emissions data was demonstrated.

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